

University of Groningen

Negligible direct radiative forcing of basin-scale climate by coccolithophore blooms

Gondwe, M.; Klaassen, Wim; Gieskes, Winfried; de Baar, Hein

Published in:
Geophysical research letters

DOI:
[10.1029/2001GL012989](https://doi.org/10.1029/2001GL012989)

IMPORTANT NOTE: You are advised to consult the publisher's version (publisher's PDF) if you wish to cite from it. Please check the document version below.

Document Version
Publisher's PDF, also known as Version of record

Publication date:
2001

[Link to publication in University of Groningen/UMCG research database](#)

Citation for published version (APA):

Gondwe, M., Klaassen, W., Gieskes, W., & de Baar, H. (2001). Negligible direct radiative forcing of basin-scale climate by coccolithophore blooms. *Geophysical research letters*, 28(20), 3911-3914.
<https://doi.org/10.1029/2001GL012989>

Copyright

Other than for strictly personal use, it is not permitted to download or to forward/distribute the text or part of it without the consent of the author(s) and/or copyright holder(s), unless the work is under an open content license (like Creative Commons).

The publication may also be distributed here under the terms of Article 25fa of the Dutch Copyright Act, indicated by the "Taverne" license. More information can be found on the University of Groningen website: <https://www.rug.nl/library/open-access/self-archiving-pure/taverne-amendment>.

Take-down policy

If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

Downloaded from the University of Groningen/UMCG research database (Pure): <http://www.rug.nl/research/portal>. For technical reasons the number of authors shown on this cover page is limited to 10 maximum.

Negligible direct radiative forcing of basin-scale climate by coccolithophore blooms

Mtinkheni Gondwe, Wim Klaassen, Winfried Gieskes, and Hein de Baar¹

Marine Biology Department, University of Groningen, The Netherlands

Abstract. The water-leaving radiance, defined as radiation from the sun reflected off particles in water and exiting the ocean surface back into the atmosphere and space, is often used to derive ocean-colour information from remotely sensed data. However, it is in itself a measure of the amount of solar irradiance reflected by oceanic constituents and, therefore, not available to the Earth's heat reservoir (changes in which can affect the Earth's energy balance and climate). A strong influence on the water-leaving radiance is observed from coccolithophore blooms, owing to the highly reflective calcareous platelets or coccoliths covering these marine algae. We analysed remotely sensed water-leaving radiances (1998-1999) over the N. Atlantic, where the blooms are spatially and temporally most abundant, and found that the direct radiative forcing of climate between 402-565 nm (the major range of optical influence) by coccolithophores in this ocean is negligible ($\sim 0.05 \text{ W m}^{-2}$ mean annually). This is in contrast to what *in situ* or laboratory measurements on the immense local intensity of coccolithophore visible light scatter in the past two decades have led us to believe.

1. Introduction

In the past two decades, numerous bio-optical studies [e.g. Holligan *et al.*, 1983; Bricaud and Morel, 1986; Balch *et al.*, 1991, 1996a, b; Ackleson *et al.*, 1994; Tyrell and Taylor, 1996; Tyrell *et al.*, 1999] have shown that marine phytoplankton, specifically, coccolithophores, locally diminish the ocean's absorption of incoming visible radiation through scattering from the oceans back to space, *i.e.* a direct negative forcing (Fig. 1). Coccolithophores form external calcium carbonate (CaCO_3) scales ($\varnothing \sim 1\text{-}10\mu$; thickness $\sim 0.25\text{-}0.75\mu$) called coccoliths, which form multiple layers and eventually detach from the cells, sometimes reaching concentrations 10-20 times that of the cells themselves [Gordon *et al.*, 1988; Balch *et al.*, 1993]. Due to the high refractive index of calcite, the coccoliths result in increased light backscatter, which, under bloom conditions, has been reported as intense discolouration of ocean surface waters (turquoise to whitish colour) by both sailors and oceanographic scientists alike. *In situ* optical measurements, laboratory experiments and satellite data analyses have provided similar reports [e.g. Holligan *et al.*, 1983; Viollier and Sturm, 1984; Balch *et al.*, 1991, 1996a, b; Ahn *et al.*, 1992; Ackleson *et al.*, 1994; Voss *et al.*, 1998]. Modelling studies [Tyrell and Taylor, 1996; Tyrell *et*

al., 1999] have shown that for a typical ocean, the proportion of photons re-emitted by ocean water increases from 0.4% when there are no coccolithophores in the water to 2% with $100 \text{ mg CaCO}_3 \text{ m}^{-3}$ (representative of coccoliths) in the water, to 5.2% with $300 \text{ mg CaCO}_3 \text{ m}^{-3}$. With the exception of these initial calculations by Tyrell *et al.* [1999], no other attempts have been made to analyse the implications of these localised backscattering effects on climate, *i.e.* at a larger scale.

2. Approach

Using above-surface normalised water-leaving radiances (henceforth nLw) measured in visible channels 1-5 of the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) aboard the SeaStar satellite, we have determined the extent to which a return of visible solar energy to space by coccolithophore blooms is significant to global climate. Our estimates improve on those by Tyrell *et al.* [1999] who modelled the effect of coccolith scattering on the albedo (glint radiance plus water-leaving radiance in Fig. 1) of a water body in order to determine the climate radiative forcing effect of coccolithophores. A shortcoming in using albedo for this purpose is that the glint radiance component of the albedo is not influenced by algal presence, but rather by illumination geometry and the slope of the water surface [Payne, 1972]. By considering only the water-leaving component of the albedo, which in Case I waters (the open ocean) is almost entirely influenced by phytoplankton presence [Gordon *et al.*, 1988; Sathyendranath and Morel, 1983; Lee *et al.*, 1994], our estimates provide a more precise quantifica-

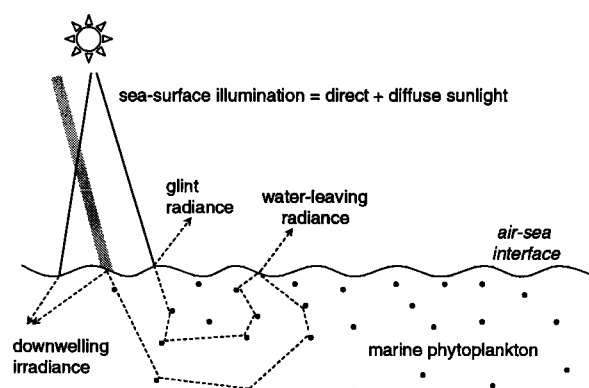


Figure 1. Influence of particles in ocean water on downwelling irradiance.

¹Also at the Netherlands Institute for Sea Research.

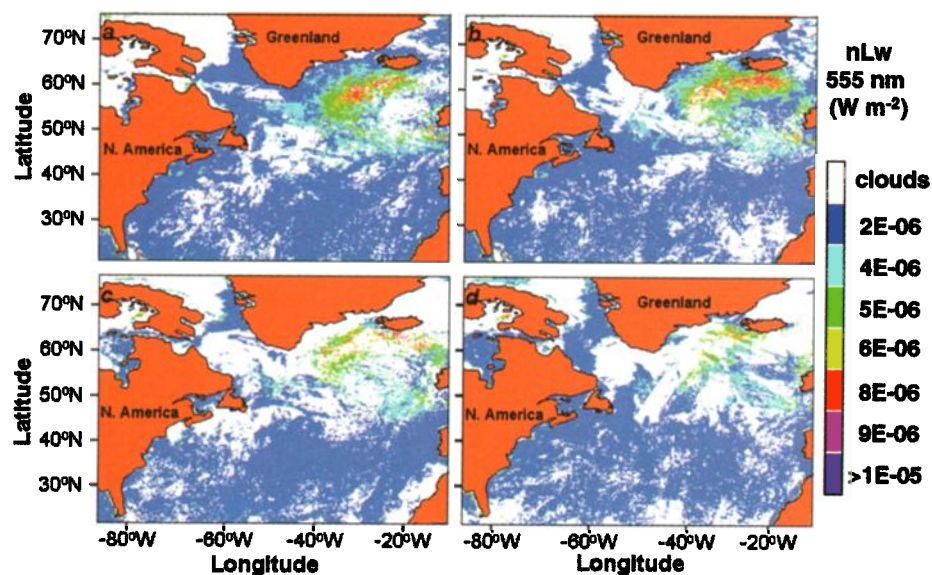


Figure 2. The growth and decay of the June 1998 coccolithophore bloom. a-d: Julian days 153-160, 161-168, 169-176, and 177-184, respectively.

tion of the direct radiative forcing of climate by these algae. Furthermore, being direct (albeit remotely sensed) measurements of the water-leaving radiance (*i.e.* actual fluxes), our data validate the theoretical results obtained by Tyrell *et al.* [1999], which are expressed in terms of percentage reflectance of photons.

The nLw data (originally expressed in milliwatts per square centimetre per micron per steradian, $\text{mW cm}^{-2} \mu^{-1} \text{sr}^{-1}$) are Level 3 equal-area gridded data at a spatial resolution of 9 km^2 . They are obtained from NASA's Goddard Distributed Active Archive Center and were atmospherically corrected from raw satellite-received radiances according to the methods of NASA's SeaWiFS Project [e.g. McClain *et al.*, 1995; Barnes *et al.*, 1996], by the project's calibration and validation team. Since daily images are problematic to analyse due to their high and spatially variable cloud coverage, analyses were conducted on 8-day composites.

The study area was the N. Atlantic ocean (23°N to 75°N ; -86°W to -7°W), with focus on Case I waters. According to Brown and Yoder [1994] and Brown [1995], the N. Atlantic ocean is the most appropriate area (spatially and temporally) for the study of coccolithophore blooms in these waters. We examined and report on a two-year (1998-99) data record, and also present analyses for the spatially extensive ($\sim 5 \times 10^5 \text{ km}^2$) coccolithophore bloom which occurred south and southwest of Iceland, in the month of June 1998 (Fig. 2).

The June 1998 coccolithophore bloom is clearly visible in all SeaWiFS imagery of water-leaving radiances in wavebands 1-5, although the intensity of the nLw varies with waveband. The presence of coccolithophore blooms was initially detected by analysing nLw at 555 nm, where backscat-

tering by ocean water is minimal, and where it is largely dominated by particulate calcite scattering when present [Holligan *et al.*, 1983; Viollier and Sturm, 1984; Balch *et al.*, 1991, 1996a, b; Ackleson *et al.*, 1994]. The spatial location of the blooms was then noted in other wavebands where their reflectance signals were not easily distinguishable from those of the ocean water itself. These other wavebands or

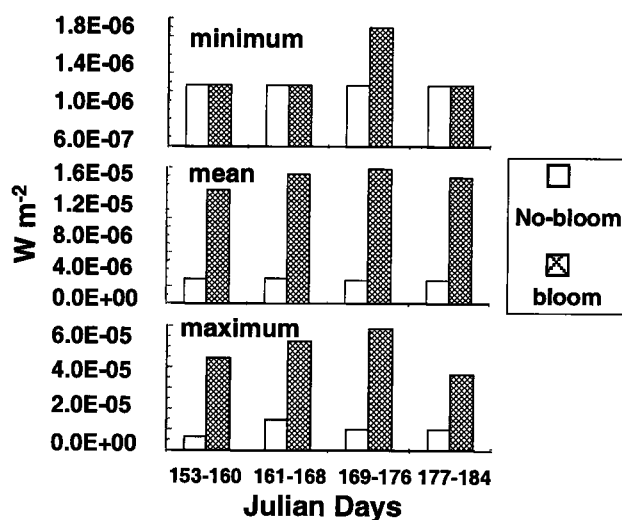


Figure 3. nLw at 555 nm over a coccolithophore bloom versus a no-bloom area. Trends at 490 and 510 nm are similar, however, those at 412 and 443 nm are only greater than those over the no-bloom area in the third week of June, when the bloom was at its most reflective.

channels are each 20 nm wide and are centred at 412, 443, 490 and 510 nm.

We quantified the phytoplankton effect illustrated in Fig. 1 by comparing nLw over the June 1998 bloom to those over an area where no algal blooms were detectable in the imagery (oligotrophic waters) (Fig. 3). In calculating the radiative forcing, the coccolithophore-contributed nLw was taken to be the difference between the nLw over the coccolithophore blooms and that over a no-bloom area of similar extent. Since there are data gaps between several of the channels in which SeaWiFS collects measurements, we linearly interpolated data to these gaps in an attempt to provide a better estimate of the total radiative forcing between 402 and 565 nm (the major range of coccolithophore optical influence). The first data gap (9 nm wide) occurs between channels 1 and 2; the second (25 nm wide) occurs between channels 2 and 3; while the third (23 nm wide) occurs between channels 4 and 5. Integration of within-channel radiances is already performed by the SeaWiFS instrument at measurement [Barnes *et al.*, 1996]. We, therefore, calculated the radiative forcing in each of the 5 SeaWiFS channels separately. The approximate total radiative forcing for each gap was taken to be the average between the approximate total radiative forcing calculated for each of the two channels flanking the gap. The sum of the individual contributions from the 5 SeaWiFS channels and 3 gaps was taken to provide an estimate of the total radiative forcing of coccolithophores between 402 and 565 nm.

3. Results and Discussion

Although we confirmed that the presence of coccolithophore blooms in the ocean does result in an intense localised return of incoming visible light energy (Fig. 3), we also found that the associated radiative forcing, at the scale of the entire ocean, is marginal. In total, the June 1998 bloom effected a local radiative forcing of $\sim 2.5 \text{ W m}^{-2}$ during its existence, while the mean annual radiative forcing effected by all coccolithophore blooms in N. Atlantic Case I waters was estimated at $\sim 0.05 \text{ W m}^{-2}$.

This marginal effect is to be expected when one also considers the spatial extent of the bloom in relation to the entire surface area of the ocean. A bloom as extensive and intense as the June 1998 bloom examined here is astounding, but significant only on a local scale. The N. Atlantic ocean covers some $\sim 36 \times 10^6 \text{ km}^2$, of which the June 1998 bloom covers only 1.4%. Only 42 other distinct blooms with differ-

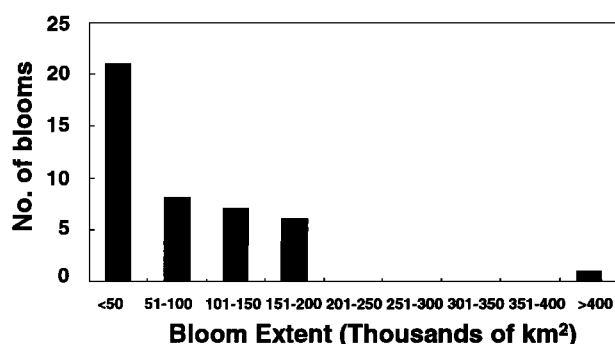


Figure 4. Spatial extents of N. Atlantic coccolithophore blooms (Sep. 1997-Mar. 2000) as detected by SeaWiFS.

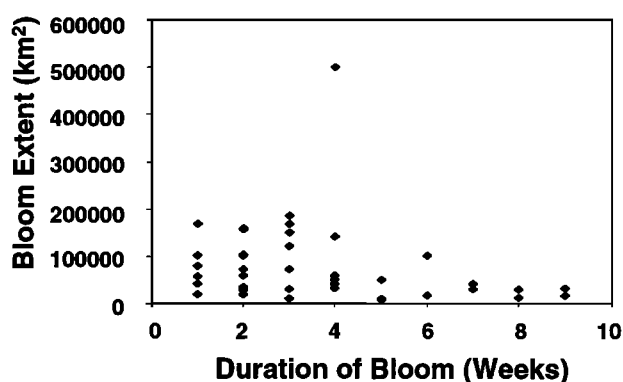


Figure 5. Duration of N. Atlantic coccolithophore blooms (visible phases only), based on spatial extent classes (Sep. 1997-Mar. 2000).

ing intensities and spatial extents varying between $\sim 8 \times 10^3$ and $\sim 1.68 \times 10^5 \text{ km}^2$ were identified in the SeaWiFS N. Atlantic dataset. Half of all identified blooms covered between 8×10^3 and $5 \times 10^4 \text{ km}^2$ (Fig. 4.), with most of these blooms covering between 3 and $3.5 \times 10^4 \text{ km}^2$. Eight, seven and six blooms fell within the $5.1 \times 10^4 - 1 \times 10^5 \text{ km}^2$, $1.01 \times 10^5 - 1.5 \times 10^5 \text{ km}^2$, and $1.51 \times 10^5 - 2 \times 10^5 \text{ km}^2$ categories, respectively. Only the bloom in June 1998 was $> 2 \times 10^5 \text{ km}^2$. At the global scale, analyses of remotely sensed data from the Coastal Zone Colour Scanner (CZCS) showed an annual coccolithophore bloom coverage of $1.4 \times 10^6 \text{ km}^2$ [Brown and Yoder, 1994; Brown, 1995]. When compared to a total surface area of the global oceans of $\sim 335 \times 10^6 \text{ km}^2$, this coverage loses significance in terms of the potential of the blooms to influence climate.

The duration and frequency of the blooms (Fig. 5) further supports the notion that coccolithophore blooms cannot be a significant role-player in the Earth's energy budget. The June 1998 bloom lasted for 4 weeks and is not an annually recurrent feature (reported only once before in 1991 [Balch *et al.*, 1996b]). Blooms between 1 and $2 \times 10^5 \text{ km}^2$ lasted 1-6 weeks, with a high tendency towards 2-3 weeks. Blooms between 5×10^4 and $9.9 \times 10^4 \text{ km}^2$ lasted 1-4 weeks. The duration of blooms $< 5 \times 10^4 \text{ km}^2$ is the most variable (1-9 weeks). These periods (visible and scattering phases only) are considerable when the blooms are viewed in isolation, but short in relation to the rest of the year when impacts are absent or much more reduced.

4. Conclusions

Numerous research efforts in the past two decades have reported intense backscattering of solar irradiance by coccolithophore blooms [e.g. Holligan *et al.*, 1983; Bricaud and Morel, 1986; Balch *et al.*, 1991, 1996a, b; Ackleson *et al.*, 1994; Tyrell and Taylor, 1996; Tyrell *et al.*, 1999]. These studies focussed on the local optical impacts of the blooms. Intense backscattering of solar irradiance by coccolithophore blooms on a local scale has the potential to affect local meteorological (e.g. wind patterns, evaporation, convection) and physical oceanographic processes (e.g. vertical mixing in the water column, currents), which may in turn be relevant to ecological issues (e.g. feedbacks of changes in water motion on plankton dynamics). In this study, we quantified

the local radiative forcing of a large coccolithophore bloom ($\sim 5 \times 10^5 \text{ km}^2$) in the N. Atlantic using satellite data. This forcing (2.5 W m^{-2} between 402 and 565 nm - the major range of coccolithophore optical influence) may be large enough to affect physical processes in the surface ocean and lower atmosphere in the vicinity of and during the bloom. Microscale meteorological and oceanographic measurements in locations of coccolithophore blooms, which were beyond the span of the current study, would be necessary to confirm these proposed linkages.

In this study, we aimed to quantify radiative forcing by coccolithophores on a larger spatial (basin-scale) and temporal scale. Our interest was to determine whether the magnitude of solar irradiance reflected by coccolithophore blooms, throughout the year, is significant enough to perturb physical processes at the climatic scale. SeaWiFS data analysis has shown that the spatial extent, frequency and duration of significantly large coccolithophore blooms relative to the area covered by the rest of the N. Atlantic ocean is marginal, and that radiative forcing of climate by the blooms is insignificant at the basin scale ($\sim 0.05 \text{ W m}^{-2}$ mean annually). Considering that blooming coccolithophores are spatially and temporally most abundant in the N. Atlantic [Brown and Yoder, 1994], one may expect the total radiative forcing at the global ocean scale not to be excessively larger than what we have calculated here. It should be noted, however, that the (albeit minimal) optical effects of ubiquitous non-blooming coccolithophores [Balch et al., 1993; 1996a, b; 1999] have not been taken into account in this study. Since they are present in sub-bloom concentrations, these particles are not detectable by satellites making their contribution to a global forcing difficult to quantify using the methodologies used in the current study.

Acknowledgments. The study was financially supported by the Space Research Organisation Netherlands (SRON Project EO-033). Level 3 mapped nLw data at 555 nm were received from S. Groom (Plymouth Marine Laboratory, U.K.) while those at 412, 443, 490 and 510 nm were received from M. Kahru (Scripps Institution of Oceanography, U.S.). These mapped products were created from binned data obtained from NASA's Goddard DAAC, courtesy of NASA's SeaWiFS Project. We are grateful to the two anonymous reviewers whose comments greatly improved this paper.

References

- Ackleson, S.G., W.M. Balch, and P.M. Holligan, Response of water-leaving radiance to particulate calcite and chlorophyll *a* concentrations: A model for the Gulf of Maine coccolithophore blooms, *J. Geophys. Res.*, **99**, 7483-7499, 1994.
- Ahn, Y.-H., A. Bricaud, and A. Morel, Light scattering efficiency and related properties of some phytoplankters, *Deep Sea Res.*, **39**, 1835-1855, 1992.
- Balch, W.M., P.M. Holligan, S.G. Ackleson, and K.J. Voss, Biological and optical properties of mesoscale coccolithophore blooms in the Gulf of Maine, *Limnol. Ocean.*, **36**, 629-643, 1991.
- Balch, W.M., K. Kilpatrick, P.M. Holligan, and T. Cucci, Coccolith production and detachment by *Emiliania huxleyi* (prymnesiophyceae), *J. Phycol.*, **29**, 566-575, 1993.
- Balch, W.M., K.A. Kilpatrick, and C.C. Trees, The 1991 coccolithophore bloom in the central N. Atlantic I: Optical properties and factors affecting their distribution, *Limnol. Ocean.*, **41**, 1669-1683, 1996a.
- Balch, W.M., K.A. Kilpatrick, P. Holligan, D. Harbour, and E. Fernandez, The 1991 coccolithophore bloom in the central N. Atlantic II: Relating optics to coccolith concentration, *Limnol. Ocean.*, **41**, 1684-1696, 1996b.
- Balch, W.M., D.T. Drapeau, T.L. Cucci, R.D. Vaillancourt, K.A. Kilpatrick, and J.J. Fritz, Optical backscattering by calcifying algae, separating the contribution of particulate inorganic and organic carbon fractions, *J. Geophys. Res.*, **104**, 1541-1558, 1999.
- Barnes, R.A., E.N. Yeh, and R.E. Eplee, SeaWiFS calibration topics I, edited by S.B. Hooker and E.R. Firestone, *NASA Tech. Memo*, 104566 (39), 1996.
- Bricaud, A., and A. Morel, Light attenuation and scattering of phytoplanktonic cells: A theoretical modelling, *Appl. Opt.*, **25**, 571-580, 1986.
- Brown, C.W., and J.A. Yoder, Coccolithophorid blooms in the global ocean, *J. Geophys. Res.*, **99**, 7467-7482, 1994.
- Brown, C.W. Global distribution of coccolithophore blooms, *Oceanography*, **8**, 59-60, 1995.
- Gordon, H.R., O.B. Brown, R.H. Evans, J.W. Brown, R.C. Smith, K.S. Baker, and D.K. Clark, A semi-analytic radiance model of ocean colour, *J. Geophys. Res.*, **93**, 10909-10924, 1988.
- Holligan, P.M., M. Viollier, D.S. Harbour, P. Camus, and M. Champagne-Phillippe, Satellite and ship studies of coccolithophore production along a continental shelf, *Nature*, **304**, 339-342, 1983.
- Lee, Z., K.L. Carder, S.K. Hawes, R.G. Steward, T.G. Peacock, and C.O. Davis, Model for the interpretation of hyperspectral remote sensing reflectance, *Appl. Opt.*, **33**, 5721-5732, 1994.
- McClain, C.R., W.E. Esaias, M. Darzi, F.S. Patt, R.H. Evans, J.W. Brown, K.R. Arrigo, C.W. Brown, R.A. Barnes, and L. Kumar, SeaWiFS algorithms I, edited by S.B. Hooker, E.R. Firestone, and J.G. Acker, *NASA Tech. Memo*, 104566 (28), 1995.
- Payne, R.E., Albedo of the ocean surface, *J. Atmos. Sci.*, **29**, 959-970, 1972.
- Sathyendranath, S., and A. Morel, Light emerging from the sea: Interpretation and uses in remote sensing, in *Remote Sensing Applications in Marine Science and Technology*, edited by A.P. Cracknell, pp. 323-357, Reidel Publishing, Dordrecht, 1983.
- Tyrell, T., and A.H. Taylor, A modelling study of *Emiliania huxleyi* in the North Atlantic, *J. Mar. Syst.*, **9**, 83-112, 1996.
- Tyrell, T., P.M. Holligan, and C.D. Mobley, Optical impacts of oceanic coccolithophore blooms, *J. Geophys. Res.*, **104**, 3223-3241, 1999.
- Viollier, M., and B. Sturm, CZCS data analysis in turbid coastal water, *J. Geophys. Res.*, **89**, 977-985, 1984.
- Voss, K.J., W.M. Balch, and K.A. Kilpatrick, Scattering and attenuation properties of *Emiliania huxleyi* cells and their detached coccoliths, *Limnol. Ocean.*, **43**, 870-876, 1998.

H. de Baar, Netherlands Institute for Sea Research, P.O. Box 59, 1790 AB Den Burg, The Netherlands.

W. Gieskes, M. Gondwe, and W. Klaassen, Marine Biology Department, University of Groningen, Kerklaan 30, 9751 NN Haren, The Netherlands.

(Received February 9, 2001; revised July 5, 2001; accepted July 17, 2001.)